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Urbanization within a Dynamic Environment: Modeling Bronze Age Communities in Upper Mesopotamia

ABSTRACT Here agent-based models are employed to explore the behavior of small communities and their associated economic systems within an area of climatically marginal environment in northern Syria and Iraq. The examples, drawn from late prehistoric and Bronze Age societies that developed at the onset of urbanization, show how small communities might respond to various resource stresses and environmental fluctuations. The computer simulations demonstrate that some households gain resources at the expense of others and the community becomes more economically differentiated through time with some households benefiting at the expense of others. The approaches discussed demonstrate that complex societies were capable of a wide range of responses to stresses that could be absorbed or amplified via a number of social, economic, or demographic processes. [Keywords: social complexity, simulation, archaeology, Bronze Age, agent-based models]

ARCHAEOLOGICAL STUDIES at the level of the site or the region are increasingly incorporating environmental change into their operating models. Unfortunately, such models often fail to fully capture the complexity of the systems under consideration. Effective models need to acknowledge a wide range of human factors that incorporate realistic mechanisms for subsistence provision, social interactions, regional and international economies, demographic factors, and human contingency. This is a tall order, and, until recently, such approaches—if they were to be of any quantitative value—were virtually impossible. Although it is true that global environmental change does have a significant effect on many dimensions of the subsistence economy as well as many other aspects of human life, it is by no means the only or even dominant factor. This article uses examples of Bronze Age communities in a marginal semiarid environment to show how environmental change can be incorporated into interpretations of human settlement. The modeling project brings together data from cuneiform texts, archaeology, landscape studies, and environment proxy records, analyzed within an agent-based modeling framework. Our group, Modeling Ancient Settlement Systems (dubbed the MASS group), consists of researchers from the Argonne National Laboratory, the University of Chicago (Oriental Institute and Department of Anthropology), and the University of Durham, together with affiliated colleagues from the private sector and other universities.

Complex adaptive systems are not simply complex. They often show a structure that relates not to "top-down processes" of control but to the operation of small-scale processes, which, in aggregate, can result in larger-scale patterns or process, often known as "emergent properties" (Bentley 2003). As a result, models can produce outcomes or structures that may have been unanticipated at the beginning. As pointed out by Henry Wright, integrating the wide range of subdisciplines that constitute the holistic discipline of anthropology can be a daunting task, although it has led to elegant, but specific, case studies (Wright 2000:373). In this article, rather than relying on either narrative force of argument or conclusive proof of relationships, we use agent-based modeling to explore the behavior of small

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communities and their agricultural subsistence systems at the onset of urbanization, operating within a climatically marginal environment.

Using the ancient Near Eastern city as a particularly well-documented example of long-term settlement, the MASS project is intended to address the following: First, how and why in the third and fourth millennium B.C.E. cities in the irrigated zone of southern Mesopotamia grew to a greater size and complexity than those in the rain-fed north; second, what was the dynamic trajectory of such settlements through time; and third, how did the resultant cities respond to a capricious natural environment and how were they able to grow, survive, or decline under various social, environmental, and economic stresses? A fundamental assumption underlying the original modeling framework was that land-use practices mediate between social groups and the environment so that crop productivity is not simply a function of environmental factors but is also dependent on numerous human decisions such as the frequency of cropping and the availability of crop amendments derived from pastoral flocks and settlement wastes. Despite their complexity, for the purposes of modeling, one can resolve the basic ancient economy into three components: staple production, the wealth or network economy, and pastoral economies (Earle 2002).[1] Of these, it is the staple production (and, to some degree, the pastoral component) that is most readily modeled in relation to environmental fluctuations.

Although climatic fluctuations must clearly have had an impact on human communities by inflicting crop failures and sometimes famines, the massive scale of cities in both northern and southern Mesopotamia must themselves have contributed significantly to the degradation of the environment and the depletion of nutrient supplies. Consequently, the archaeologist who is seeking to understand these societies within the context of global environmental change must factor both avenues of change into their models. The two-way interaction between human communities and the environment must therefore have resulted in a complex array of coevolutionary pathways and nonlinear responses.

In both northern and southern Mesopotamia, settlements attained their maximum size during the fourth or third millennium B.C.E. and some experienced a decline in either the late third or second millennium B.C.E. (Adams 1981; Wilkinson 2000a: figure 4). The city–region, in the form of the urban center with its subsidiary settlements and land-use zones, forms a more appropriate analytical unit than the city itself. Ultimately this framework of analysis can be extended still further to include a much larger interaction sphere of information and commodity flow than the city–region itself. Within such settlement land–use systems, larger centers appear to have grown partly by means of positive feedback that resulted in increasing numbers of people being attracted to the city through time. Such growth was then constrained by processes of negative feedback, so that cities appeared not to have exceeded a certain size, especially in the climatically marginal landscapes of the northern fertile crescent (Wilkinson 1994). Neighboring centers could be expected to grow in a similar manner, and a dynamic quasiequilibrium state (but not stasis) may have developed so that a series of semiautonomous "city states" appeared. Such entities were not stable, however, and as archaeological and text-based studies demonstrate, these systems were unstable in the long term and vulnerable to abrupt declines as a result of external shocks or internal malfunctions (Adams 2001:354).

The extensive literature on early state development includes a vigorous processual tradition that examines the growth and development of Mesopotamian cities and states (e.g., Adams 1966; Wright 1994), as well as empirically grounded models that seek to understand some of the factors that contribute to urban development and collapse (e.g., Blanton 2004; Weiss et al. 1993; Wilkinson 1994). Such studies are easy to critique because they rely either on the assumption that subsistence systems were to some degree dependent on a limited range of staple crops (Blanton 2004; Wilkinson 1994) or that extreme environmental catastrophes acted to precipitate urban—and, indeed, demographic—collapse (Weiss et al. 1993). Hence, Karl Butzer (1997) tackles the shortcomings of both approaches and forcefully argues that early states in the Near East formed subsystems within a network of interactions that were sustained by long-term trade, exchange, and information flow, but which could be brought down by the severance of such processes by shifts in alliances, war, or patterns of trade.

In the context of Near Eastern states nurtured on rainfed agriculture, it is significant that the process of urbanization and settlement nucleation appears to have taken place in the face of a drying climate. As land-use intensity increased as a result of population concentration, system fragility must also have increased, so that agricultural systems must have been constrained by two factors: soil moisture deficits and increased demand for food from a limited agricultural territory (Wilkinson 1997). The dynamics of early state societies therefore entailed a range of interactions between socioeconomic processes and the environment.

The topic of human–environment interactions has been gaining momentum in recent years as a result of the huge investment in environmental research. Physical scientists, especially, have examined societal collapse in the context of palaeoclimatological data, an approach that provides results of definitive appearance, couched with a degree of scientific certainty (e.g., De Menocal 2001) that is not justified by the uncertainty of some of the archaeological data employed. The fragility of such conclusions is amplified by the simplified assumptions employed that significantly underestimate the role of human agency in ancient economies. However, the effect of humans on the content of atmospheric carbon dioxide and methane can be traced back to approximately 8,000 years BP (Ruddiman 2003). Clearly if environmental scientists are seeing both significant impacts by the environment on humans (De Menocal 2001) and significant impacts by humans on the

environment (Ruddiman 2003), there is an obvious need to tackle the problem from both directions.

To avoid deterministic oversimplifications, and to accommodate both physical and social factors, the MASS project draws from a number of disciplines, including economic anthropology, cultural ecology, ecological geography, and economic history (Bayliss-Smith 1982; Dodgshon 1988; Gallant 1991; Olsson 1988; Parry 1990). Such approaches would all benefit from the inclusion of a wide range of variables (social, economic, and environmental) that could be made to interact over long periods of time within the context of a "virtual laboratory."

At the level of global change, the MASS project is examining how selected human communities respond when they are stressed by single or multiple "events" such as dry spells and intense conflicts such as wars, pestilence, and so on. We also explore how internal system dynamics can influence long-term demographic trajectories. In addition, the models factor in the decision-making capacity of individuals; this will go some way to counteract the appearance that many models appear to not only average human behavior out but also to discount the role of individual decision-making processes or idiosyncratic actions.

A first consideration is to differentiate between various sectors of the economy, specifically:

- The subsistence economy, which, being based on calorific needs and other physiological requirements, is relatively easy to model. This functionalist approach may be sufficient to model the minimal conditions under which human life can function, but it clearly fails to capture the richness and complexity of life in human communities.
- The political economy, which includes factors such as feasting, gift exchange, or various forms of symbolic gift giving. Although more difficult to deal with than the subsistence economy, these factors can be included within an agent-based model.
- Also forming part of the political economy, factors such as trade and exchange, being often external to the territory being modeled, are difficult to incorporate into models because they frequently enlarge system scale and therefore system complexity by many orders of magnitude. Additional uncertainties are also incorporated because one must be aware of the skepticism that some scholars show regarding large-scale, commercialized trade in remote antiquity. Nevertheless, we consider that it is crucial to include mechanisms of trade and exchange to some degree.

THE APPROACH

For this initial simulation, we take a pragmatic approach to modeling the development of settlement in the rain-fed zone of Upper Mesopotamia.

- First we select an existing settlement landscape-system for which we can estimate population, cultivated area, and so forth. (In this case, we use a tell of some 17 ha area, located within an archaeological landscape that has already been mapped.)
- Next, we set up a demographic model based on the assumption that the community was responsible for its own food production, agricultural production being based on agreed parameters derived from input data from archaeology, cuneiform texts, and ethnographic factors.
- A simulation is then run using existing climate proxy sequences, climate generated from a Markov process weather generator, or a Global Climate Model, which drives the crop production system, in conjunction with a selected range of social factors.
- The simulation then demonstrates how the pattern of land use evolves through time as the population changes, and it supplies basic output data on the changing demography, nutrient balance of the soils, and other parameters.

Such a settlement land–use system can then be scaled up to comprise a pattern of settlement that includes communities that develop and interact with each other over many centuries or possibly even millennia.

Because it is easier to model, we initially employ climatic data as the external variable, but the modeling framework is explicitly constructed to actively incorporate changing social, political, and economic—as well as chance—factors. Although the model may not be able to accommodate every permutation of circumstances, it is more broad based than most deterministic models and it should eventually provide an ideal laboratory for examining human–environmental systems over long periods of time.

THE RAIN-FED NORTH

The "northern model" takes into account the wide range of processes that operate within complex economies when they interact with the environment.[2] Variables such as fallow; availability of manure, dung, or wood for fuel; feed for draft animals; plant temper for mud bricks; and of course labor all contribute to the mix to make responses to environmental "events" either blurred or unpredictable. Our model will (amongst others) consider the following factors:

- Fallowing regime. Biennial fallow is considered to be the normal means of cultivating staple crops. This allows nutrients to accumulate, counteracts the build up of pests, and conserves moisture. Annual cultivation ("violation of fallow") results in increased gross production but in the long term can cause increased cropping instability (Wilkinson 1997).
- Secondary products. Staple crops supply, in addition to human food, chaff or cereal stalks as animal feed (esp. draft animals) and temper for mud brick. These inject an element of competition between different consumption sectors.
- Fuel use. When wood provides the fuel needs of a community, animal dung is available for fertilizer, but when wood resources have been exhausted, dung will be burnt for fuel and the burnt dung must then be applied to

fields as fertilizer. As population increases, fertilizer will be more in demand, but there may be less available because of competition for organic residues and manure to meet the needs of the population for both fuel and fertilizer.
- Trends in animal or flock usage and changing size of animal holdings per households.
- Exchange of staple crops and animals between households and other sectors of the community.
- Changing availability of labor, depending on family size and the availability of able bodies to contribute to the labor pool.
- Storage and withdrawals from reserves to allow for feasting, temple offerings, and so forth.
- Demographic and social factors such as marriage patterns, within and outside the kinship group.

The economies being modeled do not represent subsistence agriculture; rather, they incorporate processes such as the production of staple crops (the primary means of basic sustenance), rearing domesticated animals, various degrees of exchange, as well as tribute, gift exchange, trade, and plunder (although the degree to which formal markets were in operation is still debated). In addition to biennial fallow, the environment of northern Syria and Iraq offers a range of choices of land use, therefore land-use strategies incorporate a range of human choices and inheritance practices. The resultant evolution of land-use practices from biennial fallow can eventually produce a wide range of outcomes.

THE SOCIAL FOUNDATION: THE PATRIMONIAL HOUSEHOLD MODEL

The basic "agent" employed in the present model is the patriarchal household, which is well attested as the fundamental social and economic unit in the ancient Near East (Schloen 2001). Textual evidence shows that many kinds of common action and shared interests on the part of suprahousehold groups were symbolized in terms of membership in the same patriarchal household. The metaphorical extension of household terminology to various political, economic, and religious groups was possible because larger social groups (including entire kingdoms and empires) were thought of as consisting of many hierarchically nested households subsumed within an overarching "household" headed by a "master" or "father" (ultimately the king or a god). This recursive pattern, replicating the same familiar household structure at many different scales of measurement, conforms to the notion of "fractal" self-similarity characteristic of the global order of complex adaptive systems.

BRONZE AGE SETTLEMENT IN THE JAZIRA: THE CASE OF TELL BEYDAR

The rolling steppe of northern Iraq and Syria (see Figure 1) is scattered with numerous prominent mounds of varying size, up to 30 meters or more in height. Most of this region falls between 200 and 600 meters above sea level. Rainfall decreases from around 700 millimeters per annum in the northwest to around 150 millimeters per annum in the south along the Euphrates. The predominant form of crop husbandry remains rain-fed cultivation of wheat and barley. In the wetter areas to the north and west, there is increased cultivation of lentils, vines, olives, and even nuts, whereas toward the south and east, barley cultivation predominates. Although the conventional limit of rain-fed cultivation is between 250 and 200 millimeters per annum, cultivation of cereals can extend further south, especially where rainfall and soil moisture is concentrated along wadis (Jas 2000:249–251). Toward the south, where barley becomes the main cereal crop, pastoralism, perhaps with some seasonal cultivation, becomes the viable option (Wachholtz 1996), although the pasturing of flocks is important throughout the region.

The patterns of nucleated tell-based settlement, which started to develop in the fourth through sixth millenniums B.C.E., attained a maximum scale in the third millennium B.C.E., after which there was a period of settlement devolution and collapse that took place in the final part of the third millennium or the second millennium B.C.E. Because of the marginal nature of the climate, it is tempting to equate the settlement collapse variously dated between 2400 and 2000 B.C.E. as resulting from episodes of dry climate, which resulted in shortfalls in the production of staple crops and associated famines and population collapse (Weiss et al. 1993). Anomalies in the pattern of settlement whereby certain settlements remained occupied or even grew despite their location in dry marginal areas (e.g., Tells Sweyhat, Brak, and Mozan)—or, alternately, whereby others collapsed despite their location in relatively moist areas (e.g., Hamoukar)—suggests that the picture might be more complicated.

Here we use archaeological and landscape surveys combined with data from cuneiform texts to reconstruct the local economy and demography of a group of settlements in northern Syria. We then employ techniques of agent-based modeling to show how a similar system might respond to selected stress events.

The Archaeological Data Set: The Tell Beydar Survey

The case study region is an area of 12 kilometers radius (452 km^2) around Tell Beydar, a regional center of the mid– to late third millennium B.C.E., located in an area of steppe receiving circa 300 millimeters mean annual rainfall per annum. The Tell Beydar Survey (TBS; Wilkinson 2000b, 2002) recovered 82 sites, of which 15 were permanently occupied in the mid– to late third millennium, providing a total of 62.1 hectares of settled area in the mid– to late-third millennium B.C.E. Tell Beydar (ancient Nabada within the kingdom of Tell Brak, ancient Nagar) occupies the apex of the TBS settlement hierarchy with a total occupied area of 22.5 hectares, of which 17.0 hectares were settled. Three sites were clustered in the range of seven to nine hectares (Effendi, Hassek, and Farfara), and four around 2.5 to four hectares. At the

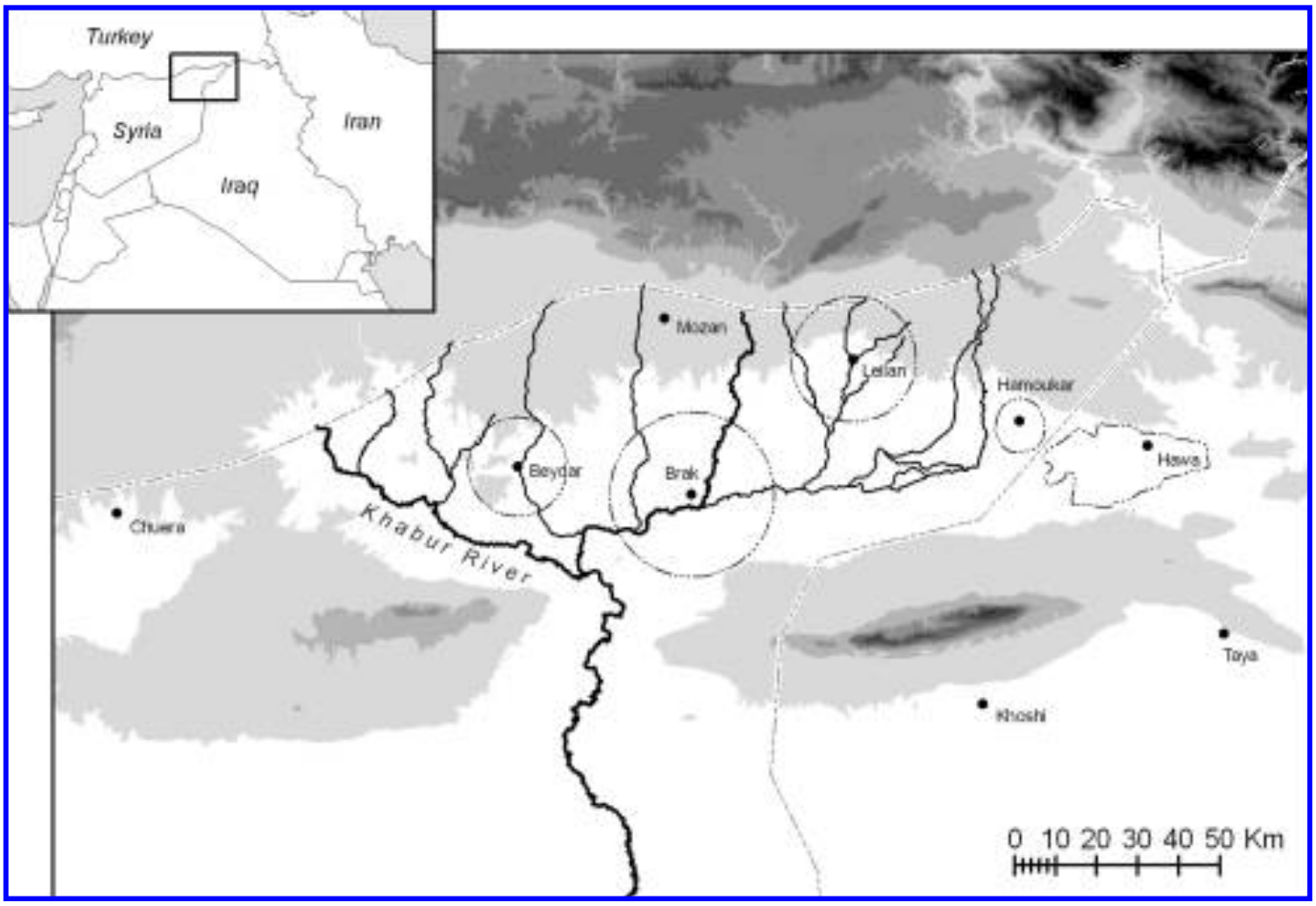

FIGURE 1. Third millennium B.C.E. sites with survey areas in Northern Mesopotamia.

base of the hierarchy were seven small villages or hamlets, all less than two hectares.

The Reconstruction of Ancient Agricultural Systems for the Tell Beydar Area

Sustaining areas provide estimates of the land required to feed the estimated site population (Adams 1981:90–94; Stein and Wattenmaker 1990). Because they assume uniformity of the surrounding soils and are based on population estimates derived from site area, they provide an oversimplified estimate of cropping capabilities and population. Moreover, they assume subsistence requirements only, and they neglect the demands from feasting, passing trade caravans, visits from royalty, and other related factors.

Initial attempts at estimating Early Bronze Age cultivation combined sustaining areas with a land-use intensity factor. Onsite population density as derived from modern and historical ethnographic analogies is generally assumed to have been between 100–200 persons per hectare, whereas the land-use intensity factor is the field area needed to support a single person for a year, this being approximately one hectare for the area in question.[3]

Figure 2a shows that there is little overlap of sustaining areas, except if population density was as high as 200 persons per hectare. Note that the estimated areas of Beydar and several other sites include cultivation on the western part of the basalt plateau, an area of thin unproductive soils that probably would have been an uncultivated pastoral zone in the Early Bronze Age. This area, therefore, should be excluded from the final estimates.

An Archaeologically Derived Cross-Check: Hollow-way Catchments

Hollow ways, which form depressions with associated soil and vegetation marks 50–100 meters wide, are interpreted as the surviving traces of former tracks that either radiated from early Bronze Age sites or connected selected sites. Significantly, these hollow ways are mainly associated with tells and occur on the cultivable plain. Only rarely do they occur on lands of lesser value for cultivation such as the basalt steppe, which provides support for the notion that hollow ways were indeed part of the agricultural landscape. They are assumed to have conveyed human and animal traffic from settlements to fields and to the pasture areas beyond (Van Liere and Lauffray 1954–55; Wilkinson 1993; Ur 2003). Hollow ways often appear to fade out at around three to five kilometers from the site, and such zones are inferred to represent the point at which fields no longer constrain traffic.

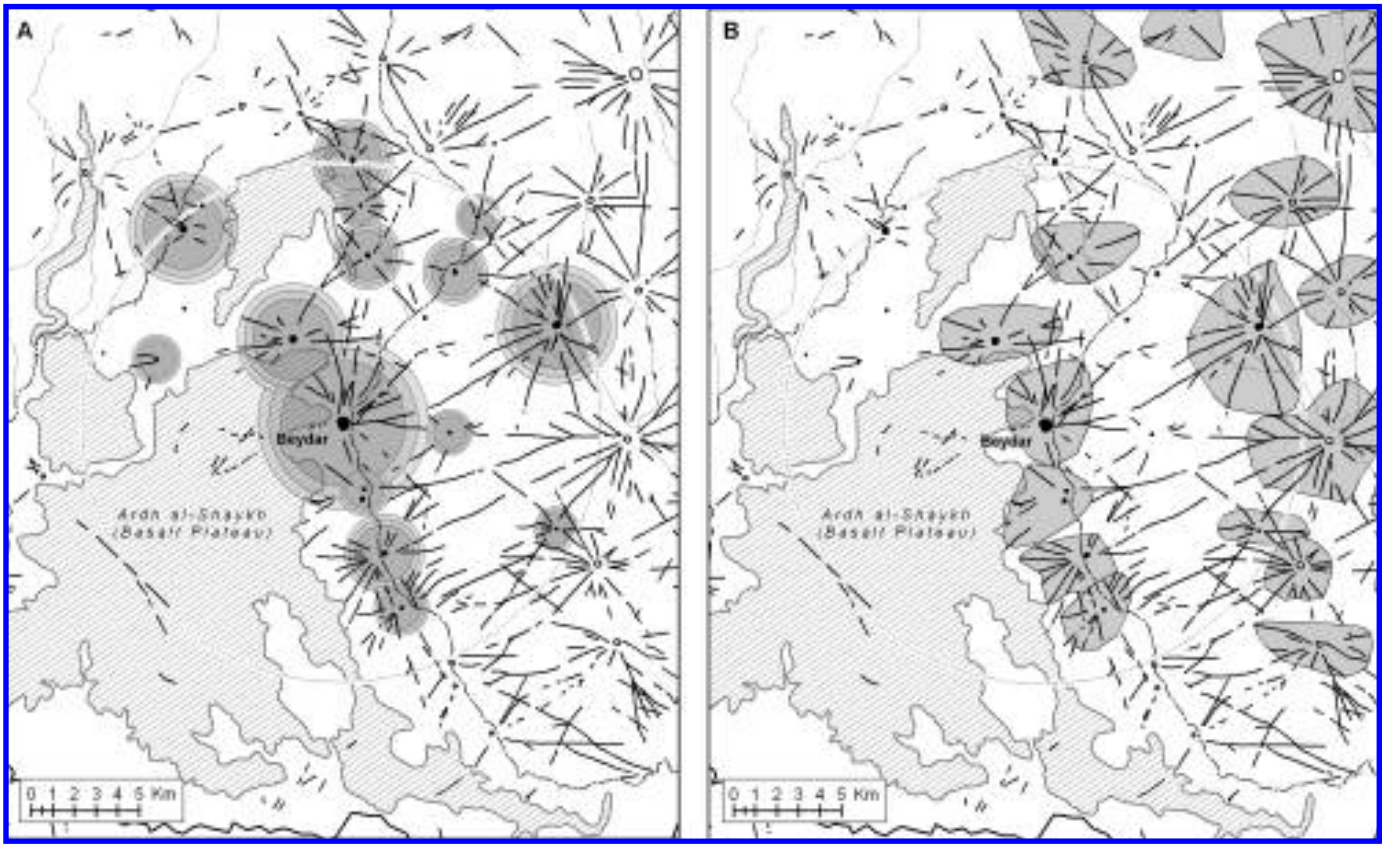

FIGURE 2. The immediate area of Tell Beydar with (A) estimated site-sustaining areas and (B) inferred cultivation from hollow ways.

Therefore, by connecting the terminal ends of the hollow ways, one can infer the boundary between the cultivated and pasture zones (Wilkinson 1993; see Figure 2b). This process involves differentiating hollow ways that served traffic to and from fields from intersite hollow ways; only the former were used to derive hollow-way catchments.

A Textually Derived Cross-Check: Plow Team Assignments

In the years 1993 to 2002, 216 cuneiform clay tablets dated to around 2400 B.C.E. (Early Dynastic IIIb) were unearthed at Tell Beydar (Ismail et al. 1996; Milano et al. 2004). Most were discovered in the "Maison aux Tablettes" in the residential Area B of the site. Almost all of the tablets, which were mainly administrative texts, concern various aspects of farming and grain management, labor, or animal husbandry.

One of the texts (Ismail et al. 1996: n. 3; see also Widell 2005) gives the number of plow animals used in Beydar as well as the number of draft animals allocated to six smaller settlements around the site. Ethnographic studies have demonstrated that oxen and donkeys are used in dual traction for plowing in Syria (see Widell 2005). According to the Beydar text, 33.5–38.5 teams of oxen and 44 teams of donkeys were utilized to till the fields directly attached to Beydar. The surrounding satellites would together have had 22–25.5 teams of oxen and 13 teams of donkeys. Note that these smaller settlements appear to have had better (stronger) teams at their disposal than Beydar itself. The higher proportions of oxen in the teams of the satellites may be an indication of less-favorable plowing conditions in these areas or perhaps the greater availability of donkeys at Beydar.

Observations from the northern parts of Jordan in the area around Irbid have provided data on the daily tillage capacity of plowing teams using the traditional symmetrical ard (Palmer 1998; Palmer and Russell 1993). Because the present environmental conditions of the area around Irbid are rather similar to those of the Upper Khabur (see Duwayri 1985:140), these data can be used to make a rough estimation of the daily tillage capacity of the Beydar teams. The data show that a team of oxen is able to till 0.3–0.4 hectares per day (8–10 hours), whereas a team of donkeys manage 0.2–0.3 hectares per day.

Studies of modern planting seasons in northern Syria and Jordan suggest that most grain in the subsistence economy of Tell Beydar was planted in November and December, and we estimate the entire plowing and sowing season to around 60 days (Widell 2005). If heavy rain sets in during the day, work is discontinued and must wait until the fields dry. Therefore, we have chosen to reduce the annual plowing season by a minimum of five and a maximum of 15 days because of rainfall. This would mean that the ancient farmers of Beydar had 45–55 available plowing and sowing

days (i.e., 50 ± 5). (It should be immediately obvious that the insertion of such arbitrary figures is rendered unnecessary by the agent-based modeling techniques discussed below.) The planting of winter crops in Syria requires two plowings; consequently, the maximum area of cultivated fields a plow team can cover will be roughly half of its actual tillage capacity. Thus, the total cultivated area for a given number of plow teams can be estimated with the following equation:

Cultivated Area (ha) = (Plow teams * Daily tillage capacity) * (50 ± 5) / 2

Using this equation with the estimates of the daily tillage capacity of the teams in our text, the area of cultivated fields directly attached to Beydar can be reconstructed to approximately 424–787 hectares, while the total tilled areas of the satellites around the site amounted to around 207–388 hectares. Using our land-use intensity factor of one (see above and n. 3), the area cultivated around Beydar would feed a population of 848–1,573 inhabitants and the surrounding satellites would feed another 414–776 people. Together, these figures presumably constitute the total agricultural area required to feed the entire population of Tell Beydar. This suggests that this total population—amounting to 1,262–2,350 people if resident at Tell Beydar—would give a total population density of 74–138 persons per hectare.

Assuming that the standard biennial fallow regime was used in the particular year of our text, the total areas of arable land would amount to around 848–1,573 hectares for Beydar and approximately 414–776 hectares for the satellites. To the arable land we must add a certain amount of wasteland that was either unsuitable or unavailable for cultivation and therefore not tilled. If we estimate that wasteland comprised 25 percent of the total agricultural area (Van Driel 1999–2000:85, n. 30), the cultivated fields, fallow fields, and wastelands around Beydar (i.e., the area covered by the radial system of hollow ways around the site) would together amount to approximately 1,131–2,097 hectares.

Synthesis of Methods

The population-derived sustaining areas for Beydar at 100 to 150 persons per hectare (2,267–3,400 ha if we include 25 percent wasteland) coincide rather well with the area estimates of cultivated land, fallow, and waste of 1,683 to 3,132 hectares as derived from the cuneiform records of plow animals for Beydar and its surrounding settlements (see below). However, the sustaining-area estimate that assumes 200 persons per hectare would have been too great for the quantity of plow animals. From the point of view of the textually based cross-check, a population density at Beydar of greater than 150 persons per hectare would not have been sustainable without the importation of agricultural products (see Figure 3).

The convergence of the data on a common territorial limit of roughly two to three kilometers radius provides a useful reconstruction of the agricultural landscape of early

Tell Beydar with satellites

	Area required to sustain the estimated site population (100–150 persons/ha)	Area estimated from all plow animals administrated by Beydar
Total land allocated (demand?)	2,267–3,400 ha	1,683–3,132 ha

Tell Beydar only

	Area estimated from Hollow Way catchment around Beydar	Area estimated from plow animals working Beydar fields
Arable land around Beydar (supply?)	1,509 ha	1,131–2,097 ha

FIGURE 3. Sustaining areas and cultivation (with waste and fallow) estimated from plow teams and hollow-way catchments.

Bronze Age Tell Beydar. Nevertheless, by using averaging methods that only deal with an assumed maximum extent of the settlement and land-use system, we fail to capture human behavior as well as evolutionary changes in land use or households. More pragmatically, few archaeological projects can muster three avenues for the estimates of settlement territories and associated carrying capacities, which would make these techniques of limited application.

COMPUTER SIMULATION PILOT STUDIES FOR TELL BEYDAR

Overview of Computer Simulation Approach

A pivotal component of the MASS group's research effort is the development of a powerful new agent-based computer simulation engine that can represent the dynamics of complex scenarios in which diverse natural and social processes operate and interact across a broad range of spatial and temporal scales. This simulation engine, dubbed "ENKIMDU," is intended to serve as an open framework within which researchers can explore alternative model formulations and hypotheses. In addition, they can observe their models' performance, sensitivities, and any interactions and feedbacks with other simulated processes, in a holistic, multidisciplinary, simulation environment.

The development of the ENKIMDU system has been supported by advanced modeling and simulation technologies developed at Argonne National Laboratory. One such enabling technology is Argonne's DIAS (Dynamic Information Architecture System; see Christiansen 2000b), a generic, object-based, computer-simulation framework, which makes it feasible to manipulate complex simulation scenarios in which many thousands of objects can interact via dozens to hundreds of concurrent dynamic processes. In addition to the DIAS system, the FACET (Framework for Addressing Cooperative Extended Transactions) framework provides a facility for constructing flexible and expressive agent-based object models of social behavior patterns (see Christiansen 2000a). By using FACET models to implement social behaviors of individuals and organizations within the context of larger DIAS-based natural systems simulations, we can conveniently address a broad range of issues involving interaction and feedback among natural and social processes.

The ENKIMDU simulations for the Beydar study address natural processes (weather, crop growth, hydrology, soil evolution, population dynamics, etc.) and societal processes

(farming and herding practices, kinship-driven behaviors, trade, etc.), interweaving on a daily basis across multidecadal to multigenerational runs. Software objects representing the salient components of the simulation domain are resolved and modeled at the level of individual persons and households, individual agricultural fields, and individual herd animals. This fine temporal resolution and fine granularity in resolving the objects and agents in the simulation domain is essential to our bottom-up modeling approach, with its search for higher-order structure as emergent behavior of an ecology of simpler households. Each of the decision-making "agents" in the simulation domain—each person, household, or other organization—governs its own behavior in the simulations based on its own local rules and in response to its own perceptions, preferences, capabilities, and goals.

The Mesopotamian simulation domain (see Figure 4) shows the major classes of entity (Field, Household, etc.) in the center of the figure; modeled dynamic behaviors of these simulation entities in the bulleted lists are indicated within each entity block. These entity behaviors are implemented by the ensemble of simulation models (shadowed blocks at the margins of the figure). The simulation software includes both custom-built models created by the MASS team and existing, off-the-shelf models that represent some of the key dynamic behaviors needed to support our dynamic "virtual ancient Mesopotamia" model. One off-the-shelf model employed within the modeling framework is the U.S. Department of Agriculture's Soil and Water Assessment Tool (SWAT) simulator (see Arnold and Allen 1992; Arnold et al. 1998). Processes addressed by the SWAT system include hydrology at individual field to watershed scale, daily agricultural weather, soil evolution and erosion, nutrient cycling dynamics, vegetation growth, grazing and browsing by livestock, and various effects of human intervention—such as tillage (leveling, plowing, planting, harrowing, harvesting, etc.) and irrigation.

Simulated interactions between natural and societal processes within the ENKIMDU framework may occur in many forms and modes. For example, Figure 5 depicts the flow of information characterizing the natural and societal process activity, which affects a simulation software object representing a single agricultural field. Figure 5 indicates that modeled natural processes can induce changes in the state of the Field object, as can the anthropogenic impacts associated with modeled agricultural and pastoral activities. In turn, because the current and subsequent states of the Field object help drive the dynamics of other processes, natural process signals can easily propagate to affect societal processes, and vice versa. Two examples illustrate this point:

- A household's work crew harvests a portion of the barley crop in a field today. As a result, the standing biomass on the field is reduced and the surface litter is increased, leading to modeled changes in the field's soil temperature profile, rate of evapotranspiration, and crop phenological growth trajectory, among other factors. In turn, the state of the crop observed by the work crew influences the household's crop management decisions.
- A shepherd leads a flock of sheep and goats belonging to multiple households onto a section of pastureland today. The livestock remove some standing biomass by foraging, trample more of it into surface litter, and fertilize the remainder by dropping manure. The subsequent complex effects of this pastoral operation on the landscape are modeled explicitly and result in locally altered soil, moisture, and vegetation state, which can be observed by the households and used to help to inform their decisions regarding continuing pasturage, breaking the fallow to plant a crop, and so on.

The patrilineal household serves as the principal class of social agent in our Bronze Age Mesopotamian simulations. Because so much of the adaptive behavior of our simulated communities is the result of household-level processes and interactions, we examine the ENKIMDU modeling representation of the household in more detail.

Modeled Household Demographics and Social Structure

The simulation system includes mechanisms for the construction of demographic and household components that are needed to characterize the population. From medieval and ancient demographic data in the Mediterranean region, we can estimate demographic trends in the preindustrial Mediterranean world (Bagnall and Frier 1994; Herlihy and Klapisch-Zuber 1985). These data match closely Ansley Coale and Paul Demeny's model life tables (Model West Levels 2 and 4 for females and males, respectively), enabling us to create demographic algorithms that can produce our model settlement's general demographic data (Coale and Demeny 1966). Names and individuals' reference numbers can be randomly created and used to trace family history throughout a simulation run. Individuals are also made aware of their interconnections with kin members, enabling lineage networks to be utilized for a variety of kin-based social behaviors.

For the present model, we consider that social interactions in Bronze Age Mesopotamia occurred primarily at the household level, with household heads making decisions affecting many or all the household members (Blanton 1994; Schloen 2001; Stone 1981). In the present simulation, individuals are assigned to households and certain resources and labor are cooperatively shared within a given household. In addition, census data from rural Ptolemaic Egypt can be used to initially reconstruct the percentages of household types potentially encountered (Bagnall and Frier 1994). Modeled basic household types are those found in the ancient Near East, including single person, nonfamily or unrelated members, nuclear, extended, and multiple-family households. Households can evolve dynamically, changing type and structure, within ENKIMDU simulations. Generally, patrilocal, multiple-family households may have been preferred; however, social stress and mortality rates may have prevented many households from achieving their ideal (Schloen 2001).

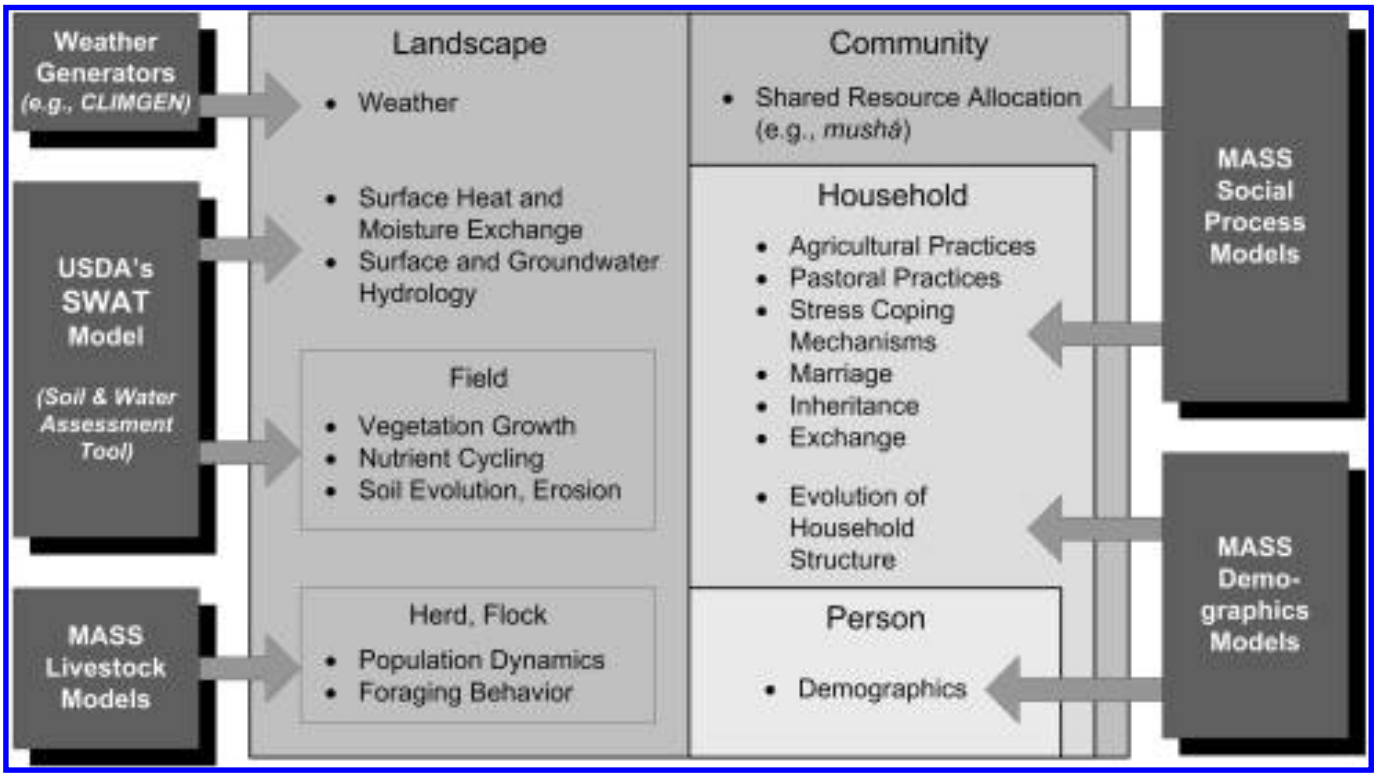

FIGURE 4. Simulation entities and dynamic behavior models for a Bronze Age Mesopotamian simulation framework.

Behaviors and decisions of households are also influenced by natural and social circumstances such as low crop yields, endogamous or exogamous marriage patterns, and high rates of death. Economic exchanges and transfers, such as bride price and dowry, reflect some of the behavioral traits associated with the marriage patterns in our present simulations (Holy 1989). For now, such exchanges of goods are limited to grain and field shares, but economic exchange is being developed as a household-based behavior to utilize kin and non-kin relationships (see below). Labor activities are organized at the household level, as is often the case in both ancient sources and ethnographies (Gelb 1979; Sweet 1974).

Household and kinship affiliations (e.g., collateral kinsmen) are key drivers and modulators of social relationships and interactions in the simulations. Thus, strengths of social and kinship ties are important in creating behavioral options for the agent households. In the current model runs, kin-related households can be called on in many cases to help alleviate a household's economic stress. However, households that provide economic support to other households may increase their influence on the community through patronage (Saller 1994; Schloen 2001). In the simulation, such mechanisms may result in the emergence of elites and political leaders.

Agricultural Practices and Activities

Nearly all households have access to cropland. Depending on the form of land tenure chosen for a simulation, fields can either be owned outright by individual households or (as in the current simulation) can be administrated under a *musha'* system. In musha', fields can be held as a community resource to be assigned annually to households by lottery, with each household receiving the use of cropland in proportion to the number of (inheritable) field shares that the household holds within the community (Granott 1952). Households that have the capacity to plant a grain crop will generally do so. Households plan and conduct agricultural activities with the goal of overproducing if possible so as to leave a safety margin. Within the agricultural year, simulated households must clear and level each field, and then plow, sow, weed and maintain, and harvest it. The labor and other resources required vary with the task (Gallant 1991; Russell 1988) and with the local context (e.g., it takes longer to plow a field if it is necessary to break fallow). Once harvest has commenced, the household's labor force must pursue the parallel tasks of processing the harvest: stacking, threshing, winnowing, and so forth. The sequences of daily crop-field management tasks are represented in detail within the ENKIMDU system's agricultural process models.

Pastoral Practices and Activities

Pastoralism was a major component of many ancient economies in the Near East, and this can be seen at Tell Beydar (Van Lerberghe 1996). Sheep and goats were often the main livestock and were not only important for their nutritional value but also for their secondary products, such as leather and wool (Zeder 1991). We simulate key aspects of pastoral behavior and allow agent households the option

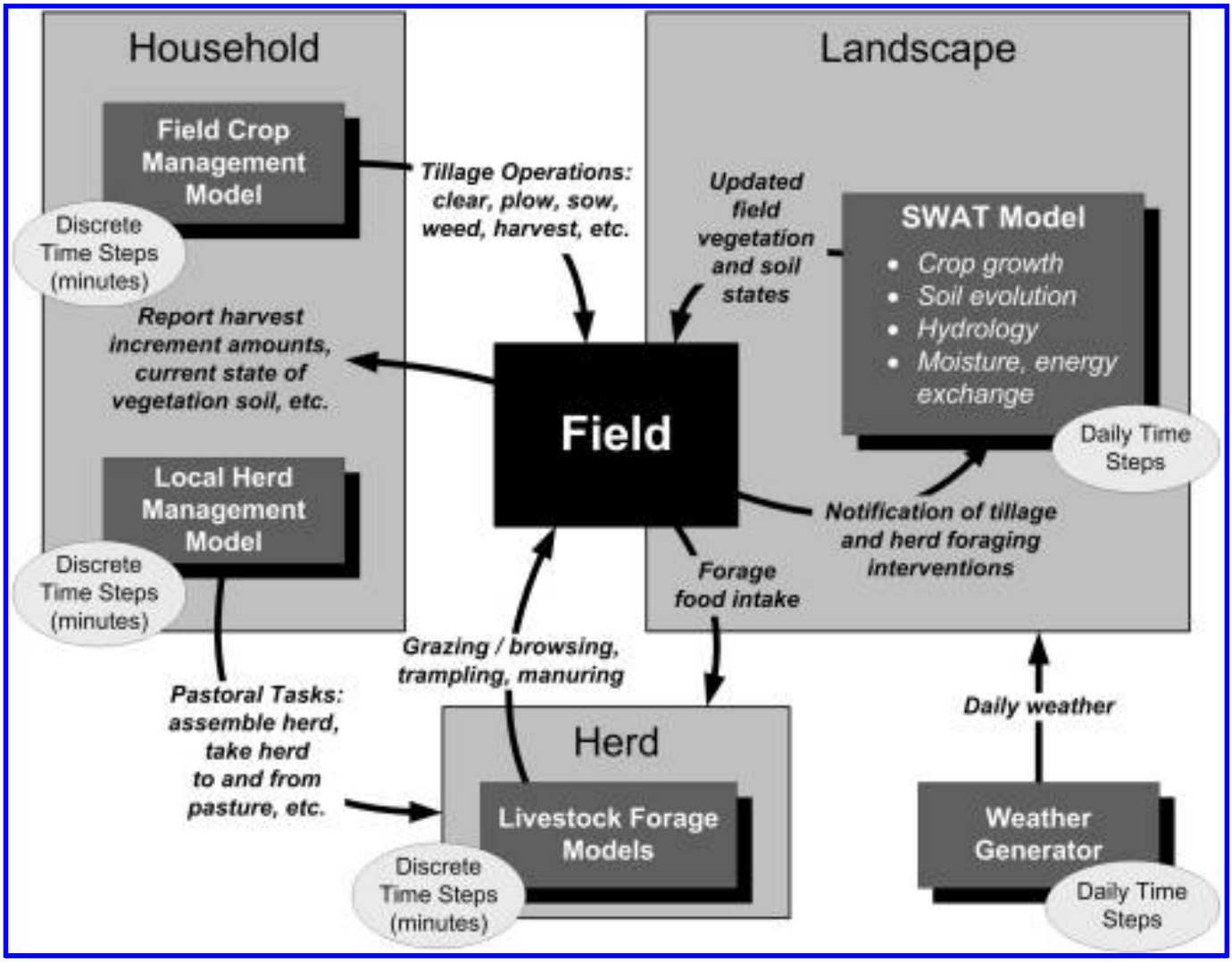

FIGURE 5. Modeling representation of a nexus for natural and social process interaction: An agricultural field.

to consider disposition of their livestock assets in making economic choices.

To address the natural systems side of pastoralism, the simulation framework presently models individual sheep and goat physiology and reproductive attributes, meat quantity at time of slaughter, and milk produced per day, as well as rates of biomass consumption and rates of manure excretion (Blaxter 1967; Redding 1981). This representation of the livestock component allows the simulation to assess positive (added manure to the soils) and negative (overgrazing) impacts on the local environment by managed herds and flocks.

On the societal side, the ENKIMDU system represents the flow of daily pastoral tasks such as herding and grazing the animals in the surrounding landscape, selecting new pastures, splitting or merging herds, and so on. Appropriate ranges of social behavior for households undertaking these tasks can, to some degree, be estimated from ethnographic sources in the Near East. From such ethnographies, it appears that households had private holdings of domesticated fauna; however, daily grazing herds were formed as cooperatives between different households (Stirling 1965; Sweet 1974). Presently, the simulation framework allows cooperative herds to be formed by several households using kin-based relations or by other social relationships.

Clearly, social behavior in managing livestock herds can vary, particularly between modern and ancient settled communities; therefore, many social practices in managing domesticated animals can be made to differ depending on the agent household's circumstances or desires. For example, in ENKIMDU at present, sheep and goats are only slaughtered for marriage feasts or famine relief; however, if households herds are too large (larger than 25 animals per household) then excess livestock are slaughtered periodically for food, with males being the first choice of slaughter.

Household Stress-coping Mechanisms and Economic Exchange

Depending on their circumstances, households have a variety of coping mechanisms available to them for dealing

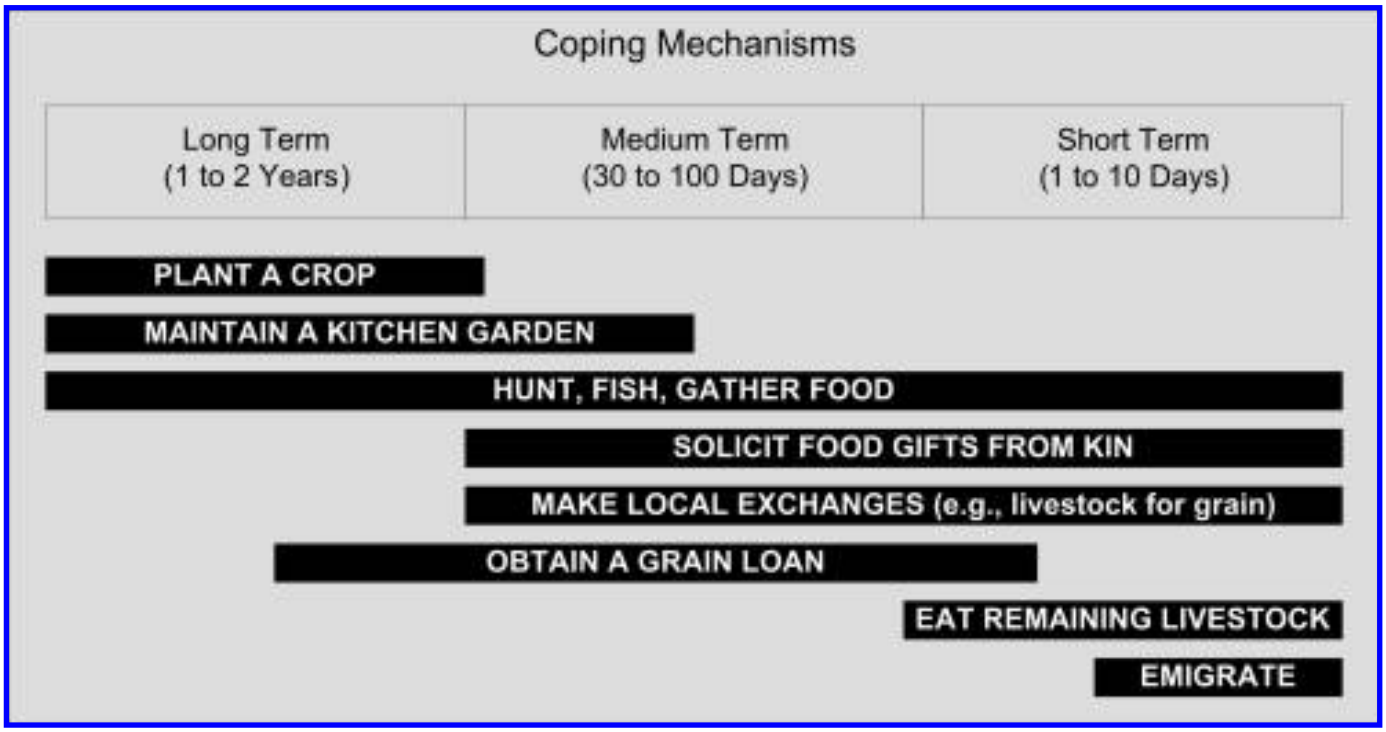

FIGURE 6. Modeled household food-stress coping mechanisms.

with periods of social or environmental stress. For instance, the formation of multiple-family households (sharing resources among related members) and livestock management (e.g., slaughtering animals in times of food stress) would have been among a range of possible options for dealing with periods of food stress (Gallant 1991; Redding 1981; Schloen 2001). Other coping mechanisms for stressful circumstances in the present simulation framework include collecting nondomesticated food sources (i.e., hunting and famine foods) and harvesting household gardens (Sweet 1974), as well as several forms of exchange of commodities among households. Emigration was usually the last option. The household food-stress coping mechanisms represented in the current ENKIMDU simulation framework are shown in Figure 6.

The current simulation allows people to choose to leave their community, as a last-ditch coping response to be taken when all other options are exhausted. In the near future, when we model multiple settlements within a region, we will integrate a representation of nomadic behavior into the simulation framework. At that point, simulated households will have sufficient context to be able to elect to emigrate to another settlement or adopt a nomadic lifestyle to improve their situation rather than simply as a last resort.

In the present modeling framework, exchange among households occurs in three forms: food gifts among close kin, small-scale trading of commodities (e.g., livestock for grain) at fixed rates of exchange, and grain loans. Households can look to better-off kin members for food gifts in times of economic stress. Such assistance is mostly in the form of gifts, with more distant kin offering less "frictionless" gifts (Netting 1968; Sweet 1974). However, households must look beyond their kin members if consanguine relations are also stressed beyond the point where assistance is feasible. Stressed households can attempt mitigating measures such as borrowing grain (due with interest after the next harvest) or selling livestock for grain outside of their kin networks. Such options are attested in cuneiform sources from the third millennium B.C.E. (Garfinkle 2004). Mutually beneficial exchanges among non-kin household agents can create or strengthen social bonds that can be used outside of kin-based networks in decision processes. For instance, non-kin bonds can support a "safety net" of households that may assist stressed households when the primary kin-based support network is inadequate.

At present, modeled interhousehold exchanges are driven primarily by need: simulated households seeking relief from food stress. Even in these limited exchange conditions, simulated households may begin to stratify by wealth to some degree as the more successful (more productive) households are able to make favorable exchanges with other heavily stressed households.

Simulation Results for the Beydar-Type Settlement

Figure 7 illustrates the spatial layout for simulations of the Beydar settlement. The modeled field layout, though algorithmically created, approximates the texture of field mosaics inferred from the landscape studies (above). "Baseline" modeling assumptions and parameterizations are noted in the figure.

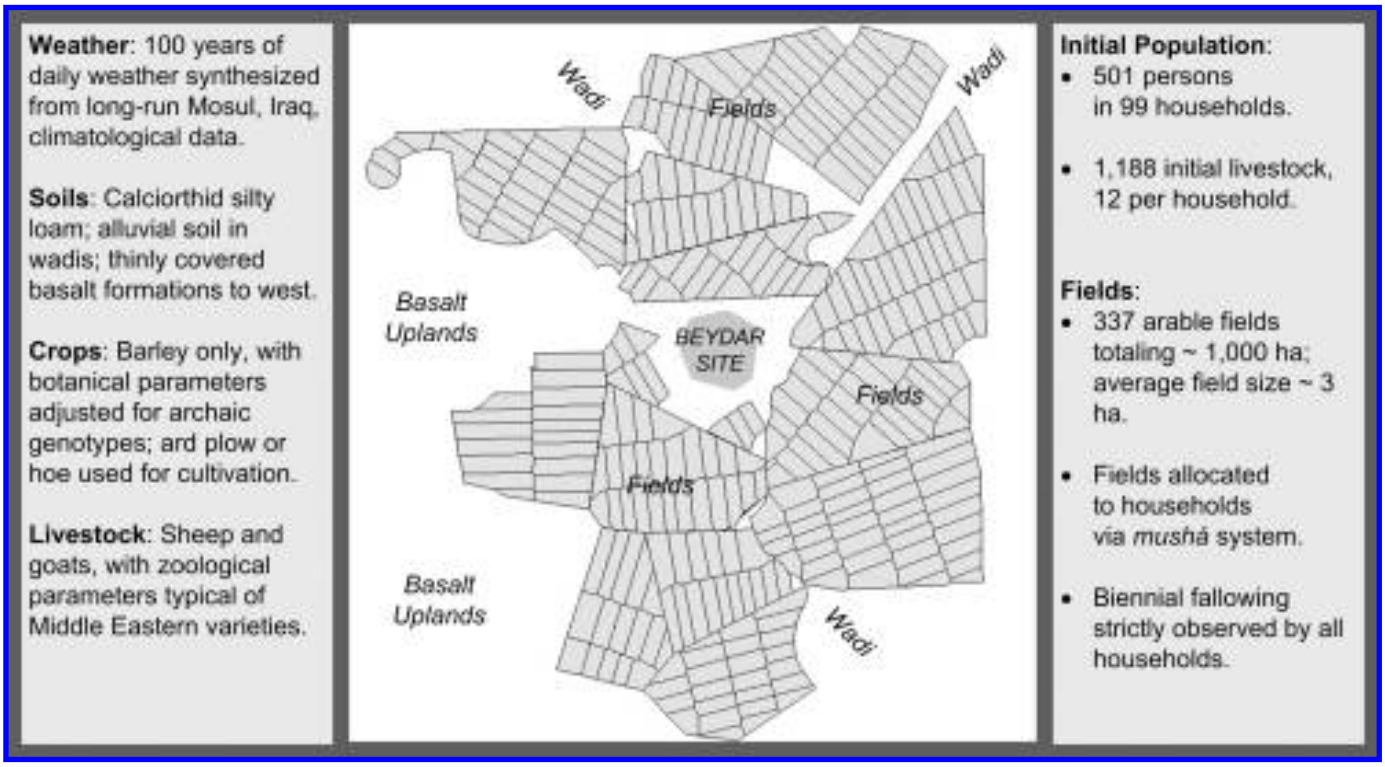

FIGURE 7. Spatial layout and initial conditions for Beydar settlement simulations.

The ENKIMDU simulation framework that generated these results is a work-in-progress, lacking robust representations of many social- and natural-system dynamic mechanisms, which we intend to incorporate. Thus, the model output shown here is intended to illustrate the sort of questions that can be addressed and to hint at the insights that may be obtainable.

We now present results from a 100-year baseline scenario simulation and from some variant scenarios. The variants are intended to illustrate effects on settlement sustainability of both chronic and episodic stresses stemming from both natural and societal causes.

One Hundred Year Baseline Results

Figure 8 presents the aggregated demographic results for the settlement across the 100-year span of the baseline simulation. Total population rises about 14 percent, from 501 initially to 569 at the end of 100 years, after peaking at 639 people, 38 years into the run. Over that same period, the number of households increased 30 percent, from 99 to 129, with a peak of 144 households occurring in the 46th year.

Total settlement births and deaths over the 100-year time span were 3,250 and 2,683, respectively. If the settlement had been a completely closed system, there would have been the potential for a doubling (at least) of the population, assuming that the agricultural capacity of the settlement catchment could support that number. However, the modeled system is not completely closed; over the course of the run, 499 people—about five per year—emigrated from the settlement, thus leaving the simulation completely. There is no external flow of persons into the settlement for our baseline scenario (this will be implemented when we move to regional, multisettlement simulations), so the settlement's net population increase is more modest.

It should be noted that emigrations are not necessarily an indication of sustainability failure of the settlement as a whole. Rather, it is a reflection of a highly localized condition: that of a household that cannot command the resources to sustain itself, even factoring in the aid of gifts from close kin, exchanges with non-kin, or loans of grain. Model results indicate that such occurrences are not unusual, even when the settlement as a whole appears to be thriving.

Figure 9 shows the simulated settlement's annual average barley yield in the context of the annual rainfall. As would be expected, the two parameters are correlated—although at +0.23 the correlation coefficient is weak. The

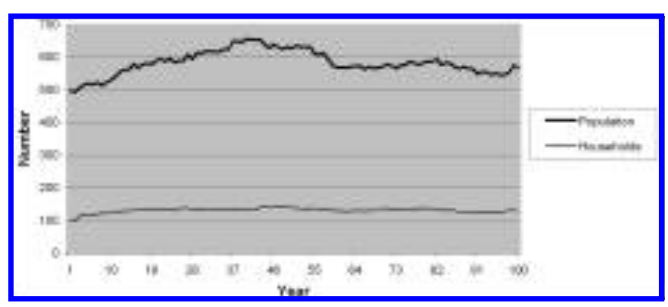

FIGURE 8. 100-Year baseline run: Total population and number of households.

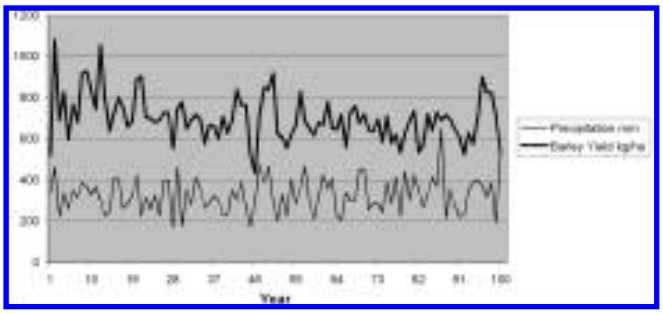

FIGURE 9. 100-Year baseline run: Barley yield and precipitation.

simulated village practiced biennial fallowing, and there was no intercropping with species other than barley. No supplemental water was applied to crops, and no manure was applied to fields other than through the agency of the settlement's livestock foraging on the fallow fields.

The results in Figure 9 reflect daily updates to the state of each of the 337 fields in the modeled settlement's surround, for 100 years of simulation: Thus, over 12 million daily field-state updates are incorporated in the yield results.

Figure 10 illustrates the relationship between the simulated settlement's total grain production and its total food consumption over the 100 years of the baseline run. In general the settlement appears to be producing a comfortable grain surplus. This tentative conclusion is reinforced by the fact that grain is not the only food consumed: Produce, meat, and dairy products make up roughly 25 percent of the diet of our simulated citizens. However, stored grain is lost to spoilage at a significant rate, and grain is also needed as seed for subsequent crops, so the surplus may not be as comfortable as it appears.

Baseline Scenario Variant 1: Chronic Harvest Blight

Here, a chronic stress in the form of a severe harvest blight was introduced. The modeled blight has a probability of occurrence of 50 percent per year, and when it does occur, it affects roughly 50 percent of the ripening grain fields. The blight is not spatially random but, rather, occurs in circular patches with radii of 1.0 kilometers; affected areas are not spatially correlated from year to year. Affected fields lose from 80 to 90 percent of their grain yield, in the month or

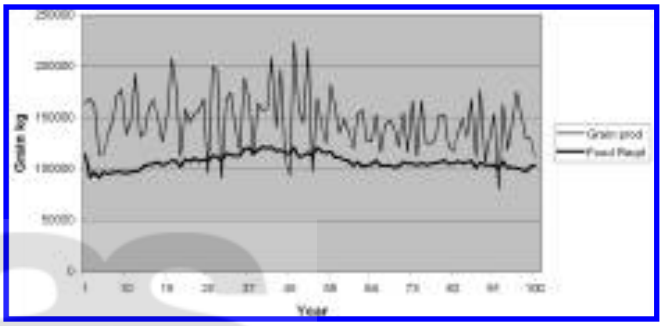

FIGURE 10. 100-Year baseline run: Trends in settlement food production and consumption.

TABLE 1. Comparison of Household Rate of Access to Exchange-Related Food Stress Coping Mechanisms in Harvest Blight and Baseline Scenarios (per year and per household)

	Livestock Sold	Grain Gifts	Grain Loans	Exchanges
Baseline Case Mean	0.0318	0.1305	0.0307	0.0630
Blight Case Mean	0.0461	01351	0.0584	0.1043
Blight/Baseline	1.450	1.035	1.902	1.656

so before harvest. Thus, the total spatially and temporally averaged effect of the blight is to reduce grain yields by roughly (0.5) × (0.5) × (0.8)—about 20 percent. The problem for the settlement community is that the blight impacts are not felt uniformly; rather, they are visited heavily on a subset of settlement households.

In the 50-year blight scenario run, the simulated settlement was significantly affected by the blight. Table 1 compares the frequency with which households resorted to exchange-related coping mechanisms in the 50-year blight case compared to the first 50 years of the baseline case. To cope with the chaotically varying crop yields they experienced in the blight case, households resorted to a markedly higher volume of grain loans (up 90 percent) and exchanges of livestock for grain (up 45 percent), though grain gifts from kin maintained a consistent level in both runs.

Ultimately, some households could not sustain themselves by applying the coping mechanisms available and were forced to emigrate. At 50 years into the simulation, the settlement population in the blight case was 452, down from the initial population of 501 and far below the baseline run's population of 628 at the 50-year mark.

Baseline Scenario Variant 2: Chronic Shortage of Plow Teams

This variant tested the resiliency of the simulated settlement to variations in a single key component in the agricultural process: households' access to plow teams. Ten-year simulations were run for three variants that differed from the base case only in the settlement's overall number of plow teams per household. The base case value was 0.5 (half as many plow teams as households). We also examined cases in which the ratio was 0.25, 0.1875, and 0.125.

Figures 11 and 12 illustrate a behavior frequently seen in complex systems: an abrupt and vivid change in aggregated system behavior as a hidden resource threshold is reached. The population traces in Figure 11 indicate that the 0.25 and 0.1875 plow team per household ratio cases appear to be sustainable, differing little from the base case. This implies that plow-team availability is not a serious constraint to successful agriculture at those resource levels. However, the simulated community in the 0.125 case (one plow team for every eight households) fails catastrophically (see Figure 11), resulting in a precipitous decline in settlement population. The main reason for this exodus can be seen in Figure 12, which depicts total area of land that was required for

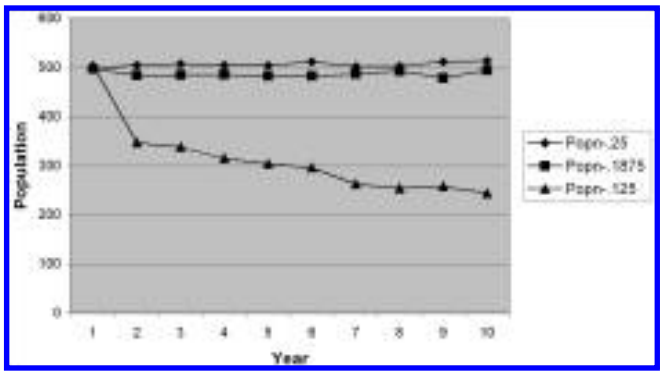

FIGURE 11. Effects of varying household access to plow teams on settlement population sustainability.

cropping but could not be plowed and therefore brought to harvest because there were insufficient plow teams. When the number of plow teams was generous (one team for less than four households), nearly every household was able to plow all of its fields as allotted each year; in fact, with more generous allocations plow teams could rest because they were surplus to requirements. As the number of households sharing each plow team increased, on average the area of land plowed per household fell below the area required to support a family. Equally, because increasing numbers of families were in a position of stress, the total area of land that could not be taken up for cultivation (because it could not be plowed) increased dramatically. The notionally "abandoned" area of land then decreases (years three to ten) simply because the number of households decreased as population declined as a result of inadequate food supplies.

This simulation highlights the critical role that plow teams play in the agricultural economy. It also shows that the simplified averages employed in the archaeological and text-based model (above) fail to incorporate the elasticity that is apparent from the simulation. However, the simulation is too mechanistic in its assumptions (a problem of our simplified notion of input data), because as the number of households sharing plow teams increased beyond the critical threshold, in reality some of the households would turn (or return) to manual cultivation by hoe or related technologies. This would not only enable more land to be returned to cultivation, but because hoe cultivation can be

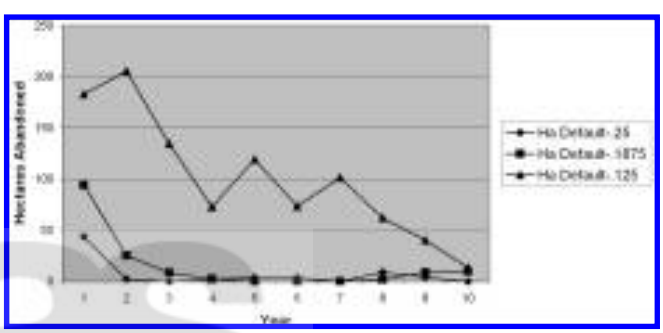

FIGURE 12. Effects of varying household access to plow teams on tillage-related crop failures.

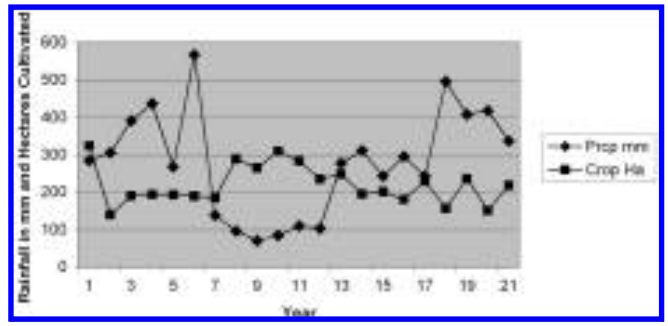

FIGURE 13. Settlement-cropping response to a five-year drought.

associated with slightly higher yields per unit area than plowing (Blanton 2004), this policy would offset the massive loss of production caused by diminished plowing capacity. Clearly future simulations should incorporate more alternative forms of soil preparation.

Baseline Scenario Variant 3: Severe Five-Year Drought

This scenario variant examines the simulated settlement's adaptive response to a severe environmental shock: in this case, a prolonged drought. As is illustrated in Figure 13, a dramatic reduction of rainfall to perilously low levels of around 100 millimeters per year was imposed on the community for simulation years eight though 12.

The climate shock in this scenario prompted several types of adaptive response by the agents. Figure 13 shows that the number of hectares cultivated in the year after the drought began increased substantially. This response was triggered by agents attempting to crop as many fields as possible to compensate for poor yields per hectare. (That this expedient proved at least partially successful can probably be attributed to the moisture-conserving fallowing practiced by all simulated households.) Conversely, the number of hectares cultivated decreased after normal rainfall amounts resumed, as crop yields per hectare returned to normal and the need to cultivate many fields subsided. Further, to combat the stress caused by the low rainfall and reduced yields, households made more use of their kin networks to share food resources. This is demonstrated in Figure 14, which shows a significant increase in gift exchanges during the drought. Other transactions increased on a per-household basis during the drought years, although the number of transactions for the other stress-coping options was less than that of kin members sharing their food resources with each other. Also, the number of transactions decreased after the first year of the drought, which perhaps can be explained by reference to the previous figure: Households seem to have adjusted to a new quasiequilibrium during the drought by consistently planting more field area in grain until the drought relaxed its grip.

The settlement appears to have absorbed the environmental shock of the five-year drought rather well, despite grain yields that dropped by 46 percent on average during

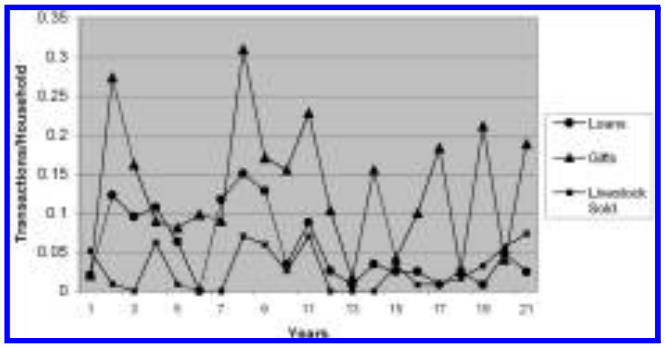

FIGURE 14. Volume of household grain gifts, livestock sales, and grain loans for a five-year drought scenario.

the drought period (from 697 kg/ha down to 376 kg/ha). Although the total population did level off for the duration of the drought, it resumed its growth at roughly the pre-drought rate once the drought was over. The demographic shift was caused by temporarily increased emigration rates, rather than declining birth rates. The rate of increase in number of households appeared to be essentially unaffected by the drought.

DISCUSSION AND CONCLUSIONS

Here the more conventional approach of modeling landscapes around the settlement provides a useful estimate of the zones of cultivation, beyond which lay presumably the pastoral lands. Clearly the populations derived by simulation (639) are well below the estimates derived from site size and catchment radius (ca. 1,700), and until we have a more complete settlement system with neighboring communities and a pool of mobile population in place, it is to be expected that population levels will continue to be modest. Rather, at this stage, these interim results may better be regarded as a barometer of community health than generators of population estimates, and it is necessary to increase simulation run time and deal with the problem of the loss of "failed households" from the system before it can be considered realistic.

Nevertheless, the use of agent-based modeling to tackle problems of human–environment interactions considerably increases the richness of any analysis. By incorporating a wide range of household size and capabilities, agent-based simulations provide a more dynamic range of outcomes than the traditional approach discussed. The simulation shows that some families gain more resources (such as animals) at the expense of others who may become impoverished. Ultimately, such differentiation will probably result in a form of social evolution in which elite groups develop and prosper at the expense of other groups that become marginalized and impoverished, and which either leave the settlement or may become clients of the more prosperous groups.

The tendency for livestock sales to peak during crises (Variant 3) is reminiscent of the famine and droughts in West Africa of the 1970s, during which peasant farmers sold their cattle to buy increasingly scarce and expensive grain (Mortimore 1989). Such droughts resulted in a sharp drop in the "price" of cattle and a massive increase in the value or price of grain. Although the role of markets in the third millennium economy continues to be debated, the operation of factors such as those that prevailed during the West African drought would result in some members of the community (those with more resources and ample food in store) becoming enriched with animals at the expense of the progressively more-impoverished peasants. Ultimately, this might result in members of such enriched families taking to the steppe to become part- or even full-time nomadic pastoralists, while perhaps retaining a foothold in the parent community. Such processes could result in significant declines in urban population and increases in nomadic pastoral groups.

One outcome of the modeling is that as a result of the employment of adaptive strategies such as exchange of surplus products, extensification of land use, and so on, it appears that population and household numbers do not necessarily decline during periods of acute drought as much as might be expected (Variant 3). This underscores a more general outcome: namely, that high-amplitude inputs (e.g., rainfall) may be absorbed by social factors to result in low-amplitude outputs (i.e., population). In the case of drought avoidance by extensification, this is only possible if it is possible to cultivate more land. However, large urban settlements (such as 100 ha Hamoukar) would be maximizing crop production to feed its 10,000-plus population, thereby limiting the options for increasing cropped area (Gibson et al. 2002; Ur 2002). In addition, if the plow animals themselves suffered high mortality rates because of the drought, this too would limit the options available. Nevertheless, there were options and these would frequently be exercised, if circumstances permitted. More generally, these results illustrate that if sufficient land is available, the most serious impacts of droughts might be avoided to some degree; if not, then crop failures would be more likely. Therefore, the situation of a run of dry years during a phase of maximum urbanization and land-use intensification might therefore be much more significant than a run of dry years where land was freely available. In other words, the increasing urbanization that occurred during the later third millennium B.C.E. in the face of a drying climate might have resulted in severe crop failures, famine, and societal collapse. However, this would have varied spatially depending on local climate, population density, trade, and wealth.

The modeling approach employed successfully demonstrates that complex societies were indeed capable of a wide range of responses to various classes of acute input variation. Clearly the above results represent only a beginning, and it is crucial not to be too naïve when interpreting the results. The mere incorporation of a factor in the model (such as exchange of animals during stress) necessarily results in such mechanisms contributing to the output. It is therefore essential to guard against circularity of argument. Nevertheless, we feel that by setting such mechanisms within a quantifiable framework, which can be tested using

numerous repeat scenarios, it should be possible to produce more reliable analyses than has traditionally been the case.

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NOTES

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1. Amended from Earle (2002); see also Sherratt (2003).

2. A model for southern Mesopotamia is currently under development to take into account the specificities of settlement development in an irrigated environment in which "low friction" canals and rivers improve the bulk transport of goods.

3. This calculation assumes an average grain yield of 500 kilograms per hectare, annual individual consumption of 250 kilograms, and the practice of biennial fallow. Thus, one hectare of arable land (cultivation and fallow) supports one person. In addition to the arable land, we estimate that an average 25 percent of northern Mesopotamia was not suitable for cultivation. Thus, the sustaining area for one person (cultivation, fallow, and waste) would be one and one-third hectares.

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